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REPORT

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Research Department, Engineering Division
THE BRITISH BROADCASTING CORPORATION February 1977

BBC RD 1977/8
UDC 621.327:
621.391.837.3:
77.019

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Summary

When a discharge lamp is run from an alternating supply, the intensity of light from the lamp varies between maximum and minimum values at twice the supply frequency. The present report analyses the film exposure variations which can occur, if such a light source is used for film lighting, when alternate intensity maxima differ in value.

Issued under the authority of

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BRITISH BROADCASTING CORPORATION

February 1977

(PH-170)

FILM LIGHTING USING METAL-HALIDE LAMPS: THE EFFECT OF INTENSITY RIPPLE ASYMMETRY

LIST OF SYMBOLS AND SUBSCRIPTS

SYMBOLS. (Subscript 'sub' indicates reference to subscript list).

$E\Big\vert_{t_1}^{t_2}$	Film exposure between times t_1 and t_2.
E_1	Film exposure for one ripple cycle.
E_N	Film exposure for N ripple cycles.
E_Q	Film exposure for fraction Q of ripple cycle.
$E'_{\max(\text{sub})}$, $E'_{\min(\text{sub})}$	Maximum and minimum exposures due to ripple asymmetry.
f_c	Camera frame frequency.
f_L, f_L'	Principal and asymmetry components of luminance fluctuation frequency.
f_p	Replay frame frequency.
f_s	Lamp supply frequency.
h	Number of complete pairs of ripple cycles.
$I_{\max 1}$, $I_{\max 2}$	Larger and smaller maximum light intensity values.
$I_{\min}$	Minimum light intensity value.
I_{mm}	Mean maximum light intensity value.
M_E	Ratio of maximum and minimum film exposure values due to presence of ripple.
$M_{E'(\text{sub})}$	Ratio of maximum and minimum film exposure values due to presence of ripple asymmetry.
m, m'	Nearest whole numbers to the number of cycles of ripple waveform and supply waveform in one cycle of camera operation.
N	Nearest whole number to the number of cycles of ripple waveform in the exposure interval.
P'	The ratio $(1-p')/(1+p')$
p	Lamp ripple ratio, $I_{\min}/I_{mm}$.
p'	Lamp asymmetry ratio, $I_{\max 2}/I_{\max 1}$
Q	Fraction of cycle of ripple waveform in, or omitted from, the exposure interval.
$R_{E(\text{sub})}$, $R'_{E(\text{sub})}$	Principal and asymmetry exposure fluctuation ratios.
$r'_{E(\text{sub})}$	Asymmetry-to-principal exposure fluctuation ratio.
S	Sensitivity factor including film speed, lens aperture etc.
t_r	Ripple period.

SUBSCRIPTS

Qd, Qi	Q-dependent or Q-independent asymmetry component.
+, –	Exposure interval somewhat longer or somewhat shorter than a whole number of ripple cycles.
Lim	Limiting value above or below which (as the case may be) picture luminance effects become perceptible.

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1. Introduction

Any discharge lamp, when run from an alternating power supply, will exhibit a variation in the intensity of the light output at twice the supply frequency (Fig. 1). When, therefore, a metal-halide discharge lamp is used as a light source for motion-picture film work, this 'ripple component' of the intensity (I_v, Fig. 1) can result in a cyclic

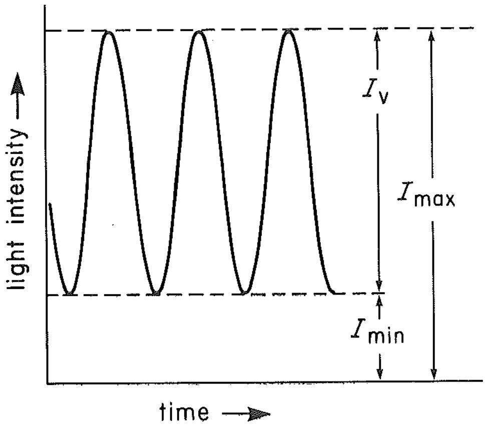

Fig. 1 - Idealised illustration of the variation in light intensity from a discharge lamp

frame-to-frame variation in film exposure, leading to a corresponding cyclic variation of overall picture luminance when the film is projected or scanned in a television system. Previous work has established limits to the permissible magnitude of variations in film exposure consistent with the resulting fluctuations in picture luminance remaining imperceptible,[1] and has outlined the relationships between the various parameters involved[2] (in particular the lamp supply frequency, the camera frame frequency, the camera shutter angle and the characteristics of the intensity ripple). In deriving these relationships it has been assumed that successive cycles of the ripple waveform are identical, as shown in Fig. 1. However, since the direction of the current through the lamp reverses for successive cycles of the ripple waveform, differences in the electrode characteristics when acting as anode or cathode for the discharge may give rise to a dissimilarity between successive ripple cycles. In practice it is found that, if this asymmetry is present, successive ripple minima may be regarded as identical, while the ripple maxima adopt alternate higher and lower values (see Fig. 4, Section 5.1). It has been previously noted[2] that this ripple asymmetry can introduce an additional component of film exposure variation, and it is the purpose of this present Report to determine the effect of this additional component in producing picture luminance fluctuations. The treatment of the subject in the present Report is based closely on (and assumes detailed knowledge of) the previously-published work.[1,2] General expressions for determining the magnitude of the effects of ripple asymmetry are derived in Section 5 (Equations (20), (30) and (36)), but discussion of these quantities involves an approximation (Equation (22)) which must be borne in mind For lamp supply frequencies in the range 45–65 Hz, camera frame frequencies of 24 Hz or 25 Hz, and for all practicable shutter angles, this approximation is valid for all cases in which picture luminance fluctuations caused by the intensity ripple component have been rendered imperceptible by the choice of suitable relationships between these parameters.

2. Terminology

In this report a number of components of exposure variation and picture luminance fluctuations are discussed. To avoid the repeated use of long descriptive phrases, the component of exposure variation caused by the presence of the intensity ripple (i.e. as discussed in Reference 2) will be termed the 'principal exposure variation component', and the fluctuations in picture luminance due to this component will be termed the 'principal luminance fluctuation component'. Similarly, the terms 'asymmetry exposure variation component', and 'asymmetry luminance fluctuation component', refer to effects caused by the presence of asymmetry in the ripple waveform. There are in fact two ways in which the asymmetry exposure variation can occur. One case (described in Section 5.2) occurs irrespective of the value (N)* of the nearest whole number to the number of cycles of ripple waveform in the exposure interval (i.e. the time interval for which the film is exposed). The magnitude of the asymmetry component in this case depends on the fraction (Q)* of ripple cycle included in the exposure interval. The other case (described in Section 5.3) occurs only for odd values of N, and gives a component whose magnitude is independent of the value of Q.

For convenience, the two cases described above are referred to as the 'Q-dependent' and 'Q-independent' asymmetry exposure variation components in the following discussion. A further distinction must be made, when dealing with the Q-dependent case, as to whether the exposure interval is longer or shorter than the nearest whole number (N) ripple cycles. It is therefore helpful to adopt a system of symbols, when discussing these cases in mathematical terms, so that similar quantities appropriate to each such case can be readily identified. The quantities in question have already been defined and discussed[1,2] in relation to the principal exposure variation component, and the same symbols as used in the previous work will be retained in this Report when referring to the principal

* The quantities N and Q equal the quantities n and q of previous work[2a] if the exposure interval is somewhat longer than the whole number N ripple cycles. For an exposure interval somewhat shorter than N ripple cycles, $N = n+1$ and $Q = 1-q$. The quantities N and Q are more easily handled when making the approximation given by Equation (22) (Section 5.2).

component. When referring to any asymmetry component a dash will be added to the symbol (e.g. p'), and a subscript will also be added made up of symbols selected from the following list:—

Subscripts 'Qd' or 'Qi' indicate the Q-dependent or Q-independent cases respectively.

Subscripts '+' or '—' indicate that the exposure interval is respectively longer or shorter than a whole number of ripple cycles.

For additional descriptive brevity these subscript symbols are also used in the text when referring to components of exposure variation or picture luminance fluctuation. For example, the 'Q-dependent asymmetry exposure variation component for which the exposure interval is longer than a whole number of ripple cycles' may be termed simply the 'Qd+' exposure variation component. The use of this abbreviated descriptive form implies reference to an asymmetry component: descriptions of principal components are not abbreviated in this way.

Limiting values of quantities, above or below which (as the case may be) picture luminance fluctuation effects become perceptible, are denoted by the addition of the subscript 'Lim', in addition to other subscripts if appropriate. Other terms used in this Report are consistent with those used in the earlier work.[1,2]

3. Picture luminance fluctuation frequencies

The frequency (f_L) of the principal luminance fluctuation component is given[2b] by the expression

$$f_L = \frac{f_p}{f_c}\left|2f_s - mf_c\right| \qquad (1)$$

where f_p is the replay frame frequency,
f_c is the camera frame frequency,
f_s is the lamp supply frequency,
and m is the nearest whole number to the number of cycles of ripple waveform in the camera operating period.

Similarly, the frequency ($f_L{}'$) of the asymmetry luminance fluctuation component is given[2c] by

$$f_L{}' = \frac{f_p}{f_c}\left|f_s - m'f_c\right| \qquad (2)$$

where m' is the nearest whole number to the number of cycles of supply waveform in the camera operating period.

From Equation (1) it can be seen that $f_L = 0$ when

$$\frac{f_s}{f_c} = \frac{m}{2} \qquad (3)$$

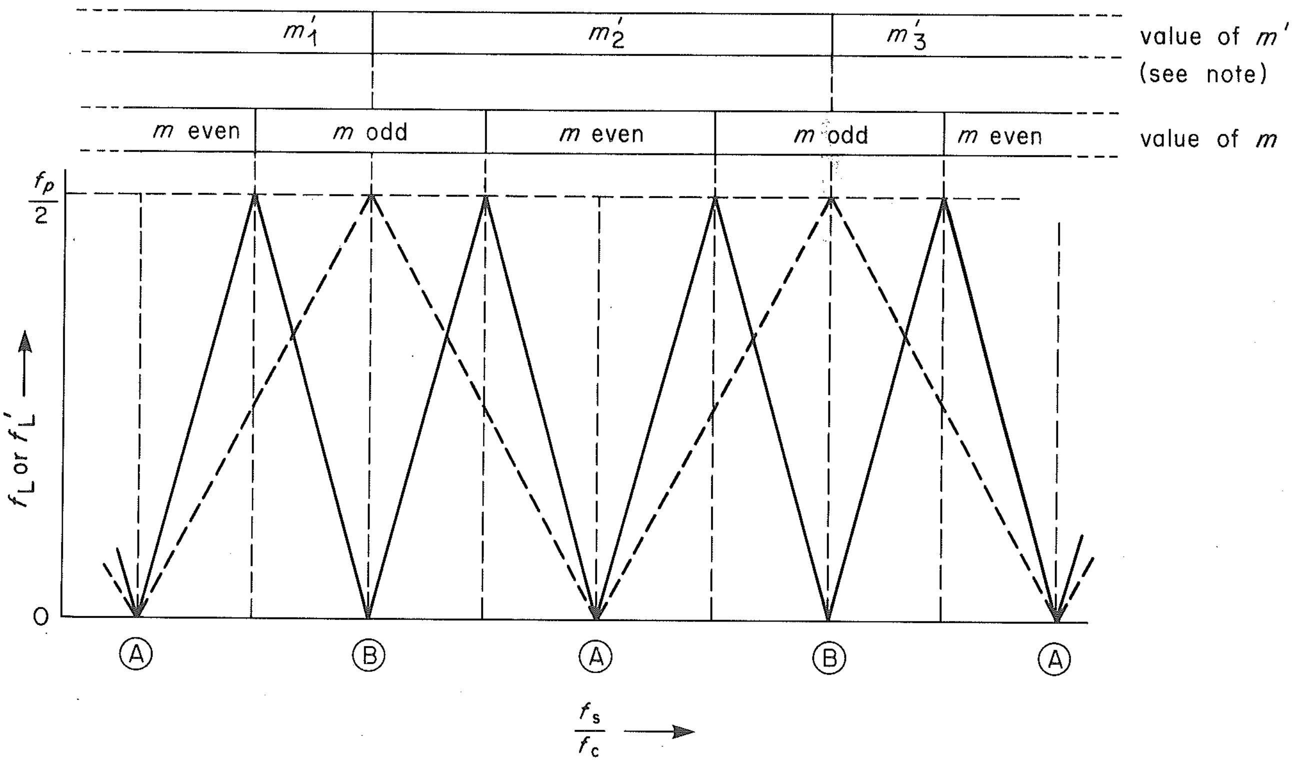

Fig. 2 - Relation between frequencies of principal and asymmetry luminance fluctuation components

——— principal component (f_L) — — — asymmetry component ($f_L{}'$)

NOTE: m'_1, m'_2, m'_3 . . . are successive integral values of m'

At points labelled Ⓐ $f_s/f_c = m'$

while $f_L = f_p/2$ (i.e. the principal exposure variation component acts so that alternate film frames receive higher and lower exposures) when

$$\frac{f_s}{f_c} = \frac{m}{2} \pm \frac{1}{4} \tag{4}$$

Thus lamp supply frequencies for which $f_L = 0$ occur at intervals of half the camera frame frequency (the integer m increasing by unity between each such frequency). Similarly, lamp supply frequencies for which $f_L = f_p/2$ also occur at intervals of half the camera frame frequency midway between the frequencies for which $f_L = 0$. Changes in lamp supply frequency of one-quarter of the camera frame frequency therefore being about successive changes in the value of f_L between zero and $f_p/2$. This relationship is shown by the full line in Fig. 2.

It can similarly be seen from Equation (2) that $f_L' = 0$ when

$$\frac{f_s}{f_c} = m' \tag{5}$$

and $f_L' = f_p/2$ when

$$\frac{f_s}{f_c} = m' \pm \frac{1}{2} \tag{6}$$

In this case changes in lamp supply frequency of one-half of the camera frame frequency bring about successive changes in the value of f_L' between zero and $f_p/2$. This relationship is shown by the dashed line in Fig. 2.

It must be remembered that two cycles of intensity ripple component occur during one cycle of the lamp sypply waveform. If, therefore, the value of m is even, then it can be seen that

$$m' = \frac{m}{2} \tag{7}$$

and examination of Equations (3) and (5) will show that $f_L = 0$ and $f_L' = 0$ for the same value of f_s/f_c. This fact is also shown in Fig. 2 at the points labelled Ⓐ. Furthermore, from Equations (1), (2) and (7) it can be seen that $f_L' = f_L/2$ in this case. A different situation however occurs when the value of m is odd. In this case Equation (7) is invalid, since m' must be integral, and must be replaced by the relationship

$$m' = \frac{1}{2}(m-1)$$

or

$$m = 2m' + 1 \tag{8}$$

If $f_L = 0$, then $f_s/f_c = m/2$ from Equation (3). Substituting the value of m shown in Equation (8) into Equation (3) gives

$$\frac{f_s}{f_c} = m' + \frac{1}{2}$$

This is a value of f_s/f_c shown by Equation (6) to give a value of f_L' equal to $f_p/2$. Hence, if m is odd, the same value of f_s/f_c gives $f_L = 0$ but $f_L' = f_p/2$. Values of f_s/f_c for which this condition applies are labelled Ⓑ in Fig. 2.

The situation may be generalised by expressing the frequency (f_L') of the asymmetry luminance fluctuation component in terms of the frequency (f_L) of the principal component. Thus

$$f_L' = f_L/2 \text{ if } m \text{ is even} \tag{9}$$

and

$$f_L' = \frac{1}{2}(f_p - f_L) \text{ if } m \text{ is odd} \tag{10}$$

4. The effect of sampling by successive film exposures

If low values of picture luminance fluctuation frequency are under consideration, each cycle of exposure variation occupies many film frames and no anomalies occur due to the effective 'sampling' of the exposure variation cycle by the exposure of successive film frames. As the fluctuation frequency increases, however, the number of film frames per cycle of exposure variation decreases until only two film frames are involved when this frequency is equal to $f_p/2$. In these circumstances the magnitude of the exposure variation between successive film frames can vary from zero to a maximum value, depending on the relative phase of the sampling times (i.e. the shutter opening times) and the intensity ripple waveform. Furthermore, if the fluctuation frequency is nearly but not quite equal to $f_p/2$, this phase relationship will change slowly and progressively and the exposure variation magnitude will similarly change between zero and the maximum value. Fig. 3 shows an example of this occurrence, obtained by computer simulation of the film exposure process. There is no evidence to suggest that the picture luminance fluctuations will be any less visible under these conditions, as compared with the case in which the exposure variation remains constant at the maximum value. The relationships derived in Sections 5 and 6, which refer to this maximum value, are therefore taken as applying to situations such as the one depicted in Fig. 3.

The exposure conditions used in deriving Fig. 3 were arranged to be such that the value of fluctuation frequency differed from $f_p/2$ by 0·25 Hz. The ripple waveform data used in the simulation related to a practical metal-halide lamp and showed some ripple asymmetry: it is of interest to note that the asymmetry exposure variation component, having a frequency half that of the principal component, can be seen at alternate higher and lower exposure values on each boundary of the 'envelope' of the principal component.

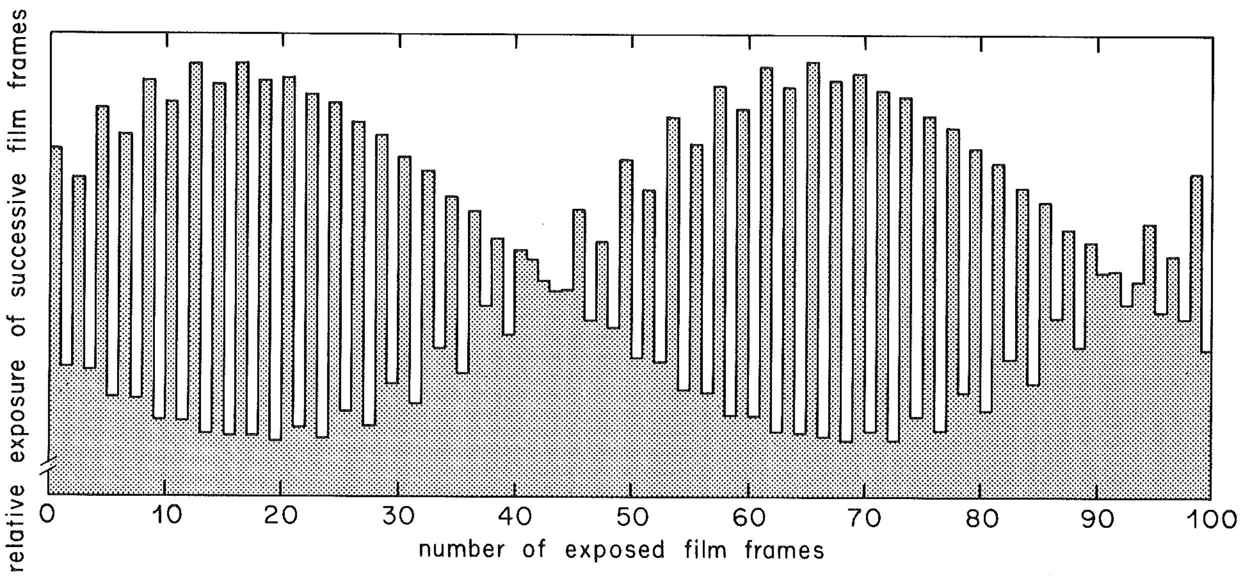

Fig. 3 - Frame-to-frame film exposure with nominal luminance fluctuation frequency near maximum possible value

5. Calculation of the magnitude of the asymmetry exposure variation component

5.1. General considerations

If ripple asymmetry is present, alternate maxima of light intensity have values $I_{max\,1}$ and $I_{max\,2}$ (Fig. 4). The

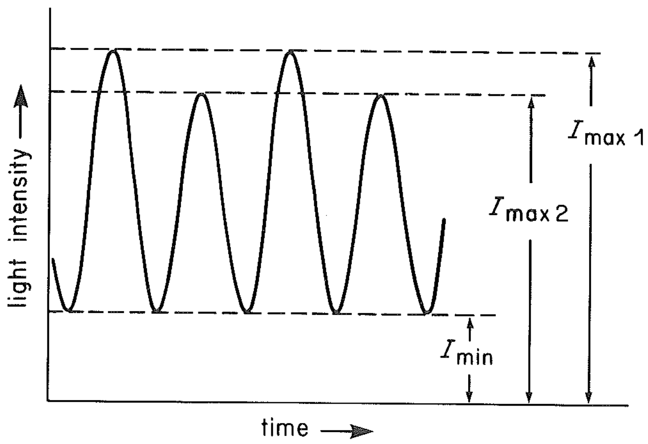

Fig. 4 - Illustration of variation in light intensity from a discharge lamp showing ripple asymmetry

minimum value of light intensity is I_{min}. The 'mean maximum' light intensity (I_{mm}) is given by the relationship

$$I_{mm} = \frac{I_{max\,1} + I_{max\,2}}{2} \tag{11}$$

If the assumption is made[2d] that each cycle of the ripple waveform is a sinusoid, the relationships describing the effect of ripple aysmmetry may be derived by the method in the previous work. If $E\Big|_{t_1}^{t_2}$ denotes the film exposure between times t_1 and t_2, then it can be shown that the exposure E_1 over one complete ripple cycle (Fig. 5), of maximum value I_{max}, minimum value I_{min} and period t_r, is given[2e] by

$$E_1 = E\Big|_0^{t_r} = \frac{St_r}{2}\,(I_{max} + I_{min}) \tag{12}$$

where S is a constant which includes film speed, lens aperture etc.

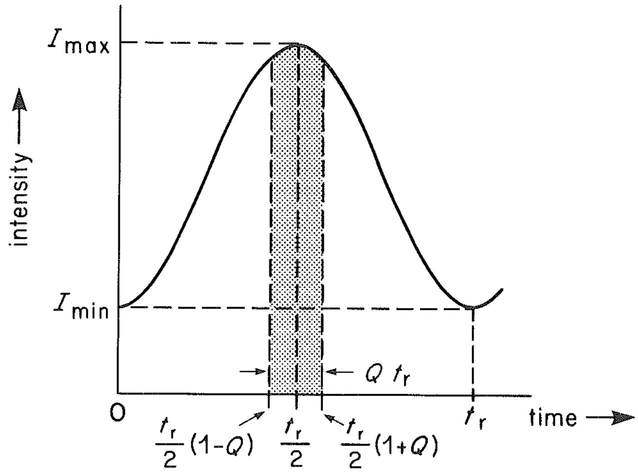

Fig. 5 - Exposure of fraction Q of a ripple cycle

Although the exposure interval is shown in Fig. 5 and Equation (12) as starting at $t = 0$ and ending at $t = t_r$, the exposure value is in fact independent of the phase of the ripple waveform at which the exposure interval starts and ends, provided that it is of duration t_r. Similarly, the exposure E_Q of a fraction Q of a ripple cycle* symmetrically positioned about the maximum of the ripple waveform, as shown in Fig. 5, is given[2g] by

* The value of Q is determined by the relationships[2f] between the lamp supply frequency, camera frame frequency and camera shutter angle (see footnote on p.1).

$$E_Q = E\Big|_{\frac{t_r}{2}(1-Q)}^{\frac{t_r}{2}(1+Q)} = \frac{St_r}{2}\left[Q(I_{max} + I_{min}) + \frac{\sin \pi Q}{\pi}(I_{max} - I_{min})\right] \quad (13)$$

Equations (12) and (13) are used in Sections 5.2 and 5.3 to determine the magnitudes of the asymmetry exposure variation components. The ripple ratio p, previously defined[2h] in the absence of ripple asymmetry, may now be re-defined in the presence of this asymmetry as

$$p = \frac{I_{min}}{I_{mm}} \quad (14)$$

5.2. The magnitude of the Q-dependent asymmetry exposure variation component

The mechanism by which the Q-dependent asymmetry exposure variation component (the 'Qd' exposure variation component: see Section 2) arises is shown in Fig. 6, for the case where the number of ripple cycles in the exposure interval (N) is equal to two, and the exposure is longer by a fraction Q of a ripple cycle than the whole number N ripple cycles. Two conditions are shown, in which the film exposure intervals start respectively near the smaller and larger ripple maxima. Because there is an even number* of ripple cycles in the exposure interval, an equal number h of smaller and larger cycles are included in it, where $h = N/2$ (i.e. h is the number of pairs of larger and smaller ripple cycles). Thus the film exposure due to the whole number of ripple cycles (light shading in Fig. 6) is the same in the two cases and independent of the phase of the ripple waveform at which this exposure begins and ends. This exposure (E_N) is given from Equation (12) by

* The case where N is odd is discussed in Section 5.3.

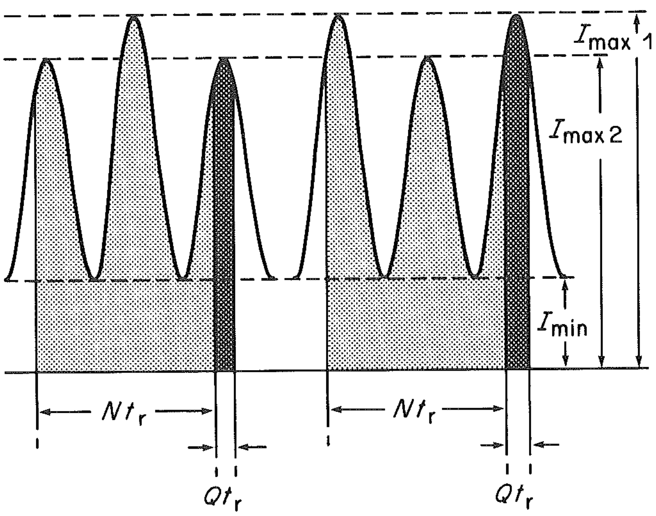

Fig. 6 - Mechanism of Q-dependent asymmetry exposure variation component

$$E_N = \frac{hSt_r}{2}\left[(I_{max\,1} + I_{min}) + (I_{max\,2} + I_{min})\right]$$

$$= \frac{NSt_r}{2}(I_{mm} + I_{min}) \quad (15)$$

The greatest difference of film exposure occurs when the fractional exposure intervals (heavy shading) are symmetrically positioned about the ripple maxima as shown in Fig. 6. From Equations (13) and (15) the maximum exposure* ($E'_{(max(Qd+)}$) is given by

$$E'_{max(Qd+)} = \frac{St_r}{2}\left[N(I_{mm} + I_{min}) + Q(I_{max\,1} + I_{min}) + \frac{\sin \pi Q}{\pi}(I_{max\,1} - I_{min})\right] \quad (16)$$

while the minimum exposure ($E'_{min(Qd+)}$) is given by

$$E'_{min(Qd+)} = \frac{St_r}{2}\left[N(I_{mm} + I_{min}) + Q(I_{max\,2} + I_{min}) + \frac{\sin \pi Q}{\pi}(I_{max\,2} - I_{min})\right] \quad (17)$$

The ratio between maximum and minimum exposure values ($M'_{E(Qd+)}$) is given by

$$M'_{E(Qd+)} = \frac{E'_{max(Qd+)}}{E'_{min(Qd+)}} \quad (18)$$

The degree of ripple asymmetry can now be defined in terms of the 'asymmetry ratio' p', where

$$p' = \frac{I_{max\,2}}{I_{max\,1}} \quad (19)$$

From Equations (11), (14) and (19) it can be seen that

$$I_{max\,1} = \frac{2}{1 + p'} I_{mm}$$

* See details of nomenclature in Section 2.

$$I_{max_2} = \frac{2p'}{1+p'}$$

and $$I_{min} = p.\,I_{mm}$$

Thus Equations (16), (17) and (18) give

$$M'_{E(Qd+)} = \frac{(1+p)(N+Q) + QP' + \dfrac{\sin \pi Q}{\pi}(1-p+P')}{(1+p)(N+Q) - QP' + \dfrac{\sin \pi Q}{\pi}(1-p-P')} \tag{20}$$

where

$$P' = \frac{1-p'}{1+p'} \tag{21}$$

Equation (20) may be further simplified by assuming that Q is small enough to write

$$\sin \pi Q = \pi Q \tag{22}$$

For values of m in the range three to five this is a valid assumption since the value of Q is constrained to be small by the necessity of keeping the principal luminance fluctuation component within the limits of imperceptibility.[3] In this case Equation (20) becomes

$$M'_{E(Qd+)} = \frac{N(1+p) + 2Q(1+P')}{N(1+p) + 2Q(1-P')} \tag{23}$$

The amount of permitted exposure variation is defined[1a] (as a function of picture luminance fluctuation frequency) for the principal exposure variation component in terms of 'exposure fluctuation ratio' R_E, such that

$$R_E = 20 \log_{10} \left(\frac{2+g_E}{2g_E}\right)$$

$$= 20 \log_{10} \frac{1}{g_E} \qquad \text{when } g_E \ll 1 \tag{24}$$

where

$$g_E = M_E - 1 \tag{25}$$

In Reference 1 the quantities under discussion were those which have been termed the 'principal components' in this present Report (see Section 2). Corresponding quantities may be defined for the asymmetry components: hence with due regard to the nomenclature of Section 2 the quantity $g'_{E(Qd+)}$ may be obtained from Equations (21), (23) and (25). Thus

$$g'_{E(Qd+)} = \frac{4Q(1-p')}{N(1+p)(1+p') + 4p'Q} \tag{26}$$

and so, from Equation (24), the 'Qd+' exposure fluctuation ratio $R'_{E(Qd+)}$ may be written as

$$R'_{E(Qd+)} = 20 \log_{10} \left\{\frac{N(1+p)(1+p') + 4p'Q}{4Q(1-p')}\right\} \tag{27}$$

If the exposure interval is shorter than the whole number N complete ripple cycles by the fraction Q of a cycle, the total film exposure during the exposure interval may be regarded as the exposure which would have occurred during the N ripple cycles less the exposure which did not actually occur during the fraction Q of a cycle. It will be appreciated that the greater exposure than occurs when the least fractional part is subtracted: that is, when the fractional exposure interval occurs at the peak of the smaller ripple cycle. Similarly, the lesser exposure occurs when the fractional exposure interval occurs at the peak of the larger ripple cycle. Thus by analogy with Equations (16) and (17) but with due regard to sign and to the nomenclature of Section 2

$$E'_{max(Qd-)} = \frac{St_r}{2}\left[N(I_{mm} + I_{min}) - Q(I_{max_2} + I_{min}) - \frac{\sin \pi Q}{\pi}(I_{max_2} - I_{min})\right] \tag{28}$$

and

$$E'_{min(Qd-)} = \frac{St_r}{2}\left[N(I_{mm} + I_{min}) - Q(I_{max_1} + I_{min}) - \frac{\sin \pi Q}{\pi}(I_{max_1} + I_{min})\right] \tag{29}$$

Thus, using the same analytical method as used to derive Equation (20), it follows from Equations (18), (28) and (29) that

$$M'_{E(Qd-)} = \frac{(1+p)(N-Q) + QP' - \dfrac{\sin \pi Q}{\pi}(1-p-P')}{(1+p)(N-Q) - QP' - \dfrac{\sin \pi Q}{\pi}(1-p+P')} \tag{30}$$

where P' is as defined by Equation (21)

while if Q is as before assumed to be small enough to enable the sine approximation (Equation (22)) to be made

$$M'_{E(Qd-)} = \frac{N(1+p) - 2Q(1-P')}{N(1+p) - 2Q(1+P')} \tag{31}$$

Thus by analogy with Equations (23) – (27), the 'Qd–' exposure fluctuation ratio $R'_{E(Qd-)}$ may be written as

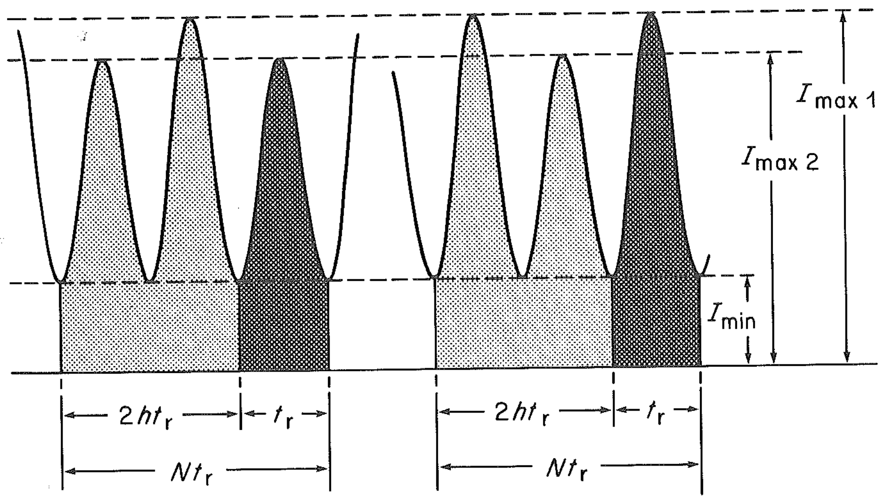

Fig. 7 - Mechanism of Q-independent asymmetry exposure variation component

$$R'_{E(Qd-)} = 20\log_{10}\left\{\frac{N(1+p)(1+p') - 4Q}{4Q(1-p')}\right\} \qquad (32)$$

5.3. The magnitude of the Q-independent asymmetry exposure variation component

If the nearest whole number (N) to the number of ripple cycles in the exposure interval is odd, the exposure interval may (depending on the relative phase of the exposure interval and the ripple waveform: see Section 5) contain an 'extra' larger or smaller ripple cycle (Fig. 7: heavy shading). This situation is independent of the presence of any fractional part of a ripple cycle in the exposure interval, and produces the greatest magnitude of exposure variation when the exposure interval starts and ends at a ripple minimum.* The number of pairs of larger and smaller ripple cycles (h) is in this case given by

$$2h + 1 = N \qquad (33)$$

Thus, following the method of analysis given in Section 5.2, referring to Equation (12) of Section 5.1, and observing the nomenclature of Section 2, the maximum exposure is given by

$$E'_{max(Qi)} = \frac{St_r}{2}\left[2h(I_{mm} + I_{min}) + I_{max\,1} + I_{min}\right] \qquad (34)$$

while the minimum exposure is given by

$$E'_{min(Qi)} = \frac{St_r}{2}\left[2h(I_{mm} + I_{min}) + I_{max\,2} + I_{min}\right] \qquad (35)$$

From Equations (33) – (35) it follows that

$$M'_{E(Qi)} = \frac{(1+p')[p + (N-1)(1+p)] + 2}{(1+p')[p + (N-1)(1+p)] + 2p'} \qquad (36)$$

* In contrast to the Q-dependent component, whose magnitude is greatest when the exposure interval starts and stops near ripple maxima.

Note that the relationship shown by Equation (36) does not involve the approximation given by Equation (22). From Equation (36), and by analogy with Equations (23) – (27), the 'Qi' exposure fluctuation ratio $R'_{E(Qi)}$ may be written as

$$R'_{E(Qi)} = 20\log_{10}\left\{\frac{(1+p')[p + (N-1)(1+p)] + 2p'}{2(1-p')}\right\}$$

$$= 20\log_{10}\left\{\frac{[N(1+p) - 1] + p'[N(1+p) + 1]}{2(1-p')}\right\} \qquad (37)$$

6. Comparisons of the principal and asymmetry exposure variation components

6.1. The principal exposure variation component

The ratio between maximum and minimum film exposures (M_E) in the case of the principal exposure variation component has been derived elsewhere.[21] In terms of the quantities used in the present Report the value of M_E is given by the relationship

$$M_E = \frac{(1+p)(N+Q) + \dfrac{\sin \pi Q}{\pi}(1-p)}{(1+p)(N+Q) - \dfrac{\sin \pi Q}{\pi}(1-p)} \qquad (38)$$

Equation (38) may be simplified by a process of analysis similar to that given in Section 5.2, and using the sine approximation of Equation (22). For brevity only the result of this analysis will be quoted: thus the principal exposure fluctuation ratio in the case where the exposure interval is somewhat longer than the N ripple cycles (R_{E+}) is given by

$$R_{E+} = 20\log_{10}\left\{\frac{N(1+p) + 2pQ}{2Q(1-p)}\right\} \qquad (39)$$

while when the exposure interval is somewhat shorter than N ripple cycles the exposure fluctuation ratio (R_{E-}) is given by

$$R_{E-} = 20 \log_{10} \left\{ \frac{N(1+p) - 2Q}{2Q(1-p)} \right\} \tag{40}$$

6.2. The relationship between the limiting value of exposure fluctuation ratio and luminance fluctuation frequency

Recommended limits on permissible exposure variations have been derived elsewhere[1a] and are reproduced in Fig. 8. The limits are given in terms of exposure fluctuation ratio as defined in Equation (24), and are equally valid

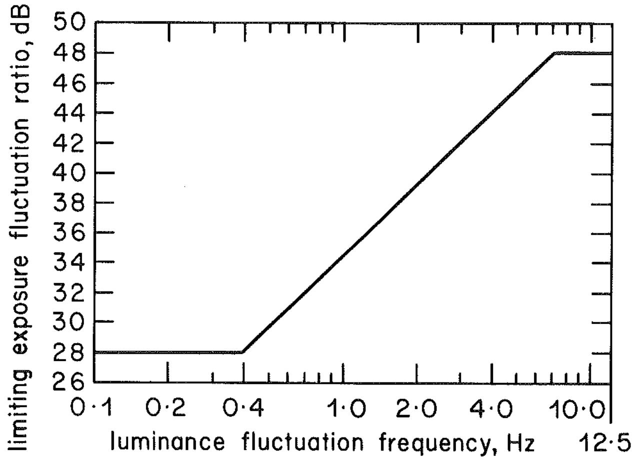

Fig. 8 - Exposure variation limits

for principal and asymmetry components of exposure variation. Thus the ordinate values refer equally to $R'_{E(Qd+)}$ (Equation (27)), $R'_{E(Qd-)}$ (Equation (32)), $R'_{E(Qi)}$ (Equation (37)), as well as to R_{E+} (Equation (39)) and R_{E-} (Equation (40)). An assumption is however made that the overall effect of picture luminance fluctuations is determined solely by that component of luminance fluctuation for which the value of exposure fluctuation ratio exceeds the limit given by Fig. 8 (thus taking into account the frequencies of the different components) to the greatest extent. Thus if the principal exposure fluctuation ratio is arranged to adopt the limiting value, it is assumed that an asymmetry luminance fluctuation component is negligible if its corresponding exposure fluctuation ratio is higher* than the limiting value in Fig. 8, and is predominant if this ratio is lower than the limiting value. This assumption provides an easily-determined criterion for assessing the relative importance of the various exposure variation components, but it must be emphasised that this validity has not been subjected to any practical tests.

* Remember that higher values of exposure fluctuation ratio imply smaller exposure variations.

6.3. Comparisons between the principal and the Q-dependent asymmetry exposure variation components

The relative magnitudes of the principal and Q-dependent asymmetry expsoure variation components may be examined by comparing the respective values of exposure fluctuation ratio. For the purposes of this comparison Equation (27) may be simplified by omitting the '$p'Q$' term in the numerator, so that

$$R'_{E(Qd+)} = 20 \log_{10} \left\{ \frac{N(1+p)(1+p')}{4Q(1-p')} \right\} \tag{41}$$

Equation (39) may similarly be simplified by omitting the 'pQ' term in the numerator, so that

$$R_{E+} = 20 \log_{10} \left\{ \frac{N(1+p)}{2(1-p)} \right\} \tag{42}$$

It should be noted that these approximations can give errors in the values of exposure fluctuation ratio of the order of 1 dB and the use of Equations (41) and (42) for calculating these values is not advised. As the approximations involved in deriving these two equations cause similar decreases in the values of both $R'_{E(Qd+)}$ and R_{E+}, however, the difference of these two quantities can be found with reasonable accuracy from them. Thus

$$R'_{E(Qd+)} - R_{E+} = 20 \log_{10} \left\{ \frac{(1+p')(1-p)}{2(1-p')} \right\} \tag{43}$$

It can similarly be shown, by omitting the terms in Q in the numerators of Equations (32) and (40), that

$$R'_{E(Qd)} - R_{E-} = 20 \log_{10} \left\{ \frac{(1+p')(1-p)}{2(1-p')} \right\} \tag{44}$$

Since the right-hand sides of Equations (43) and (44) are identical, the distinction as to whether the exposure interval is somewhat greater than or less than a whole number of ripple cycles may be discounted. Thus

$$R'_{E(Qd)} - R_E = r'_{E(Qd)} = 20 \log_{10} \left\{ \frac{(1+p')(1-p)}{2(1-p)} \right\} \tag{45}$$

where $r'_{E(Qd)}$ may be termed the 'q-dependent asymmetry-to-principal exposure fluctuation ratio'.

Equation (45) shows that the value of $r'_{E(Qd)}$ depends only on the magnitude of the ripple and asymmetry ratios (Equations (14) and (19)). It is independent of both N and Q and therefore of the relation between lamp supply frequency, camera frame frequency and camera shutter angle.[2f] Since for values of p' near unity $(1+p') \sim 2$, and thus the argument of the logarithm in Equation (45) approximates to $(1-p)/(1-p')$, it is evident that $r'_{E(Qd)}$ will in practice always be positive, since p' is always greater

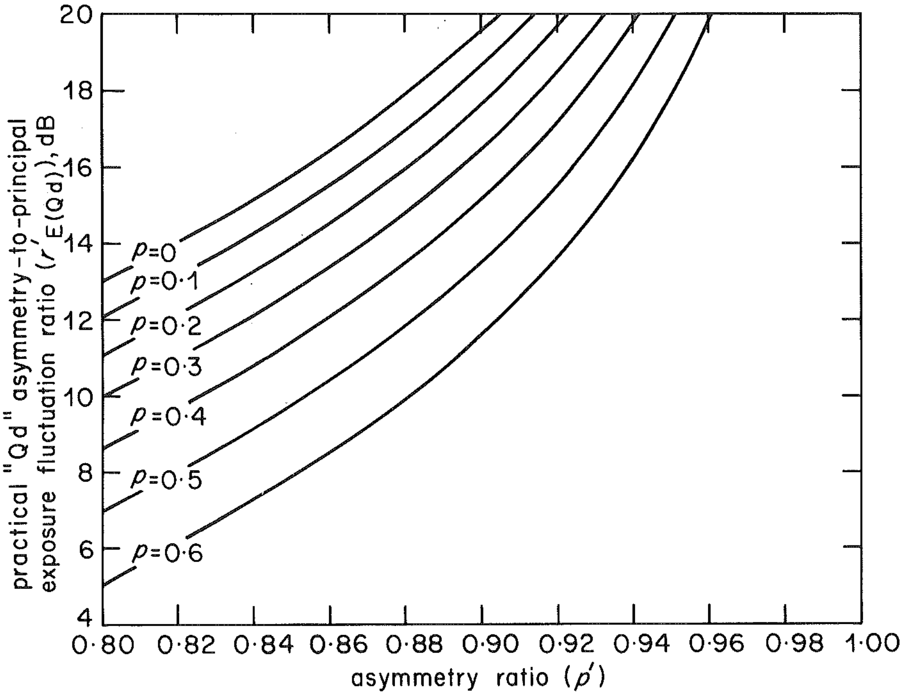

Fig. 9 - Practical Q-dependent asymmetry-to-principal exposure fluctuation ratio

than p. This indicates that the 'Qd' exposure fluctuation ratio is always greater than the principal exposure fluctuation ratio (in other words, there is always less 'Qd' exposure variation component than principal component).

Fig. 9 shows the relationship between $r'_{E(Qd)}$ and various values of asymmetry and ripple ratios. The significance of these relationships may be discussed in terms of the dependence of the visibility of picture luminance fluctuations on the frequency of such fluctuations. The limiting value of the principal exposure fluctuation ratio ($R_{E(Lim)}$) may be obtained from Fig. 8 knowing the principal luminance fluctuation frequency (f_L). The 'Qd' luminance fluctuation frequency (f_L') may now be calculated from Equations (9) or (10) depending on whether m is even or odd respectively. Again using Fig. 8, the limiting value of the 'Qd' exposure fluctuation ratio ($R'_{E(Qd\ Lim)}$) may be found knowing this value of f_L'. The difference between $R'_{E(Qd\ Lim)}$ and $R_{E(Lim)}$ may be expressed as in the left-hand portion of Equation (45): thus

$$R'_{E(Qd\ Lim)} - R_{E(Lim)} = r'_{E(Qd\ Lim)} \qquad (46)$$

It can now be seen whether the value of $r'_{E(Qd\ Lim)}$ lies above or below the practical value $r'_{E(Qd)}$ obtained from Equation (45) or Fig. 9. If m is even, the value of $r'_{E(Qd\ Lim)}$ will always be negative or zero, since $f_L' = f_L/2$ and therefore $R'_{E(Qd\ Lim)} \leqslant R_{E(Lim)}$. Since $r'_{E(Qd)}$ is always positive, as discussed above, it follows that the value of $r'_{E(Qd)}$ will always be greater than the value of $r'_{E(Qd\ Lim)}$. This indicates that when m is even, the presence of the Q-dependent asymmetry component may be ignored. On the other hand, if m is odd, then $f_L' = ½(f_p - f_L)$ (Equation (10)) and therefore $f_L' \geqslant f_L$. Since (Fig. 8) the limiting value of exposure fluctuation ratio increases with frequency, the value of $r'_{E(Qd\ Lim)}$ from Equation (46) will be positive or zero and thus may exceed the value of $r'_{E(Qd)}$ as calculated from Equation (45) or as shown in Fig. 9. If this occurs the 'Qd' exposure variation component will predominate in producing picture luminance fluctuation effects. Thus in Fig. 9, if the relevant curve falls below the horizontal line corresponding to the value of $r'_{E(Qd\ Lim)}$, then the 'Qd' exposure variation component will predominate. For example, when the frequency of the principal luminance fluctuation component is zero, the frequency of the 'Qd' component has the value $f_p/2$, thus enhancing the visibility of the 'Qd' component to the fullest extent. From Fig. 8 it can be seen that the value of $r'_{E(Qd\ Lim)}$ is 20 dB. This is of course a 'worst case' condition, and if this criterion is satisfied the 'Qd' exposure variation component will never predominate. The intersection of the curves in Fig. 9 with the line $r'_{E(Qd)}$ = 20 dB gives the relationship

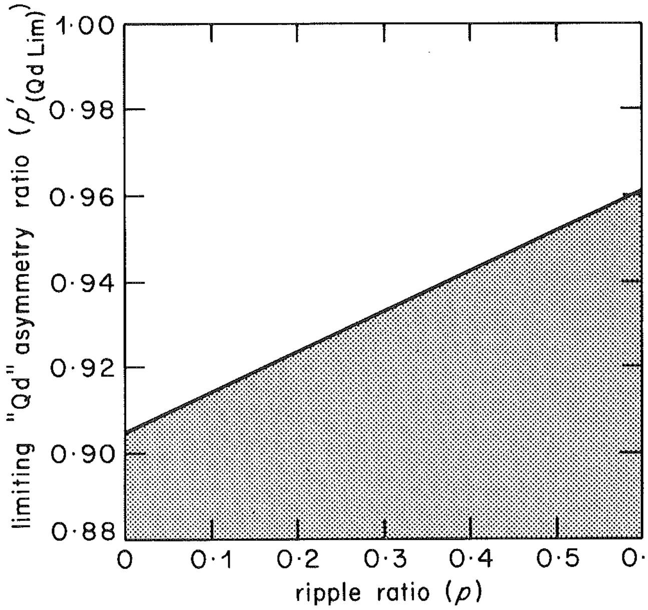

Fig. 10 - Limiting Q-dependent asymmetry ratio

$$p'_{(\mathrm{Qd\ Lim})} = \frac{19 + p}{21 - p} \qquad (47)$$

where $p'_{(\mathrm{Qd\ Lim})}$ is the limiting Q-dependent asymmetry ratio. The significance of this quantity is shown in Fig. 10. Lamps for which points with co-ordinates (p, p') lie in the unshaded area of this figure will not (when the value of N is even) be subject to picture luminance fluctuation effects due to ripple asymmetry, if the appropriate steps are taken to ensure that the ripple component itself does not produce such effects. Note, however, that when N is odd, the effect of the Q-dependent component described above will be masked by the much greater effect of the Q-independent component (See Section 5.3 and 6.4).

6.4. The effect of the Q-independent asymmetry exposure variation component

The magnitude of the 'Qi' exposure variation component, which is of importance for odd values of N (see Section 5.3), does not depend on the detailed relationships between lamp supply frequency, camera frame frequency and camera shutter angle which control the magnitude of the principal exposure variation component. It is therefore more convenient to discuss the absolute value of the 'Qi' exposure variation component, rather than its value relative to the principal component, as was done in the case of the 'Qd' component (Section 6.3). The limiting absolute value of the 'Qi' exposure variation component ($R'_{\mathrm{E(Qi\ Lim)}}$ may be found from Fig. 8 by using Equations (9) or (10)

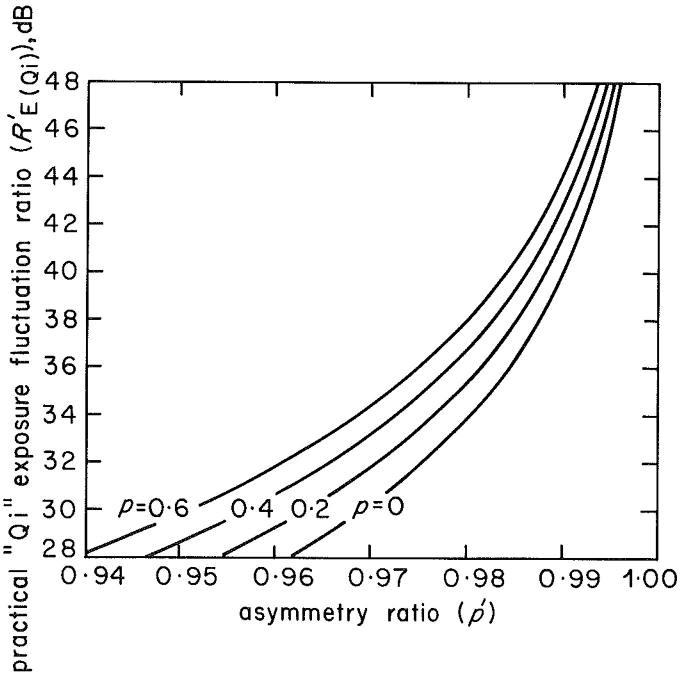

Fig. 11 - Practical 'Qi' exposure fluctuation ratio, N = 1

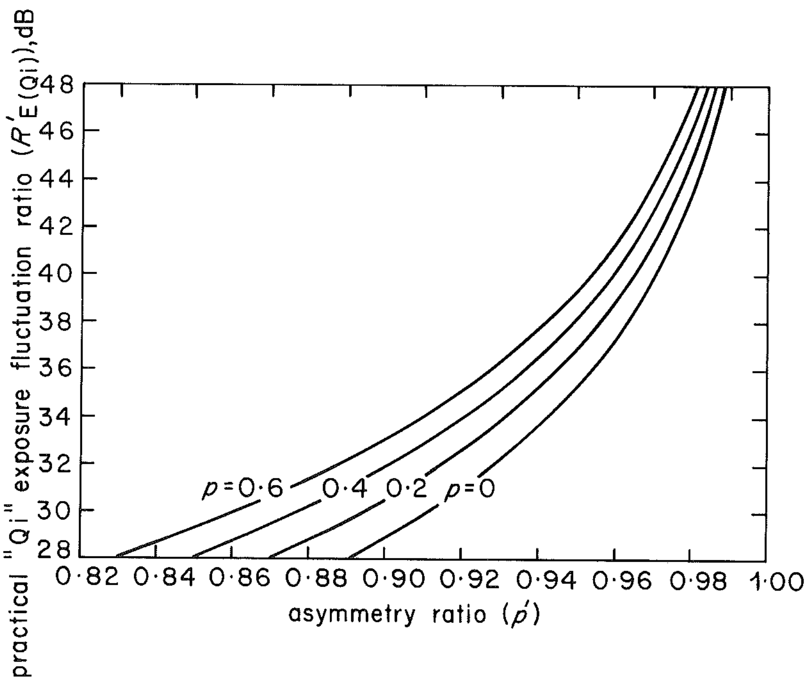

Fig. 12 - Practical 'Qi' exposure fluctuation ratio, N = 3

(depending on whether m is even or odd) to derive the frequency of the 'Qi' picture luminance fluctuations. The exposure fluctuation ratio that is obtained in practice ($R'_{E(Qi)}$) is given by Equation (37) and is shown in Figs. 11 and 12 for the practical cases $N = 1$ and $N = 3$. It can be seen that for a given value of p and p', the value of $R'_{E(Qi)}$ for the case when $N = 1$ is approximately 10 dB higher than when $N = 3$.

The practical values of $R'_{E(Qi)}$ obtained from Figs. 11 and 12 for particular values of N, p and p' may now be compared with the limiting value $R'_{E(Qi,Lim)}$ obtained from Fig. 8. If $R'_{E(Qi)}$ is lower than $R'_{E(Qi\ Lim)}$, picture luminance fluctuations due to the 'Qi' exposure variation component are liable to be visible, irrespective of the behaviour of the principal component. For example, consider (as in Section 6.3) the 'worst case' condition in which the value of m is odd, and therefore that the luminance fluctuation frequency due to the 'Qi' exposure variation component is of the order of $f_p/2$. Fig. 8 shows that the value of $R'_{E(Qi\ Lim)}$ under this condition is 48 dB. The limiting values of Q-independent asymmetry ratio ($p'_{(Qi\ Lim)}$)* for this condition are shown by the full lines in Figs. 13 and 14 for the cases $N = 1$ and $N = 3$ respectively. Comparing each of these relationships with the corresponding case (Fig. 10) for the 'Qd' exposure variation component, it will immediately be apparent that in both cases the degree of ripple asymmetry that can be tolerated in the 'Qi' case is very much less than in the 'Qd' case. From these theoretical considerations it seems that picture luminance fluctuation effects will almost inevitably occur (see Section 6.5) if conditions are such that the values of m and N are both odd, and this regime of operating conditions should therefore be avoided if at all possible.

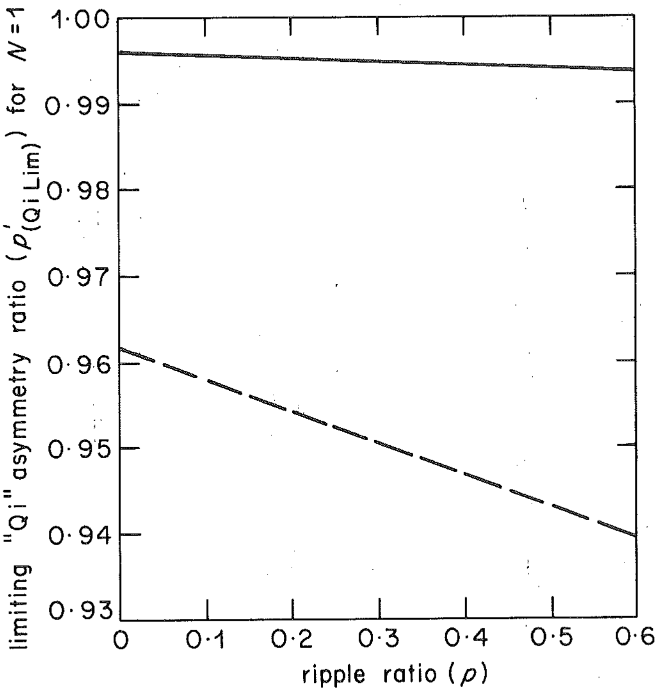

Fig. 13 - Limiting Q-independent asymmetry ratio, for N = 1
——— $R'_{E(Qi\ Lim)} = 48$ dB – – – – $R'_{E(Qi\ Lim)} = 28$ dB

If m is even, thus permitting a restriction of the frequency (f_L') of the 'Qi' luminance fluctuation component to below 0·4 Hz, the required value of $R'_{E(Qi\ Lim)}$ is 28 dB from Fig. 8. Values of $p'_{(Qi\ Lim)}$ can also be derived for this 'best case' condition and such relationships are shown by the dashed lines in Figs. 13 and 14. As would be expected, more ripple asymmetry (i.e. lower values of p') can be tolerated before picture luminance fluctuations due to the 'Qi' exposure variation component become evident, but in the case of $N = 1$ the permissible amount of ripple asymmetry is still small, being less (for values of p less than 0·45) than can be tolerated in the 'worst case' Q-dependent situation (see Fig. 10). In the case of $N = 3$ the permissible amount of ripple asymmetry is much greater, but it must be remembered that this is a 'best case' condition and the restriction of f_L' to below 0·4 Hz may impose more stringent restrictions on the relationship between lamp supply frequency and camera frame frequency than is required to ensure that the principal luminance fluctuation component remains imperceptible.

6.5. Relation between ripple aysmmetry effects and practical parameters

When using metal-halide discharge lamps supplied at

* analogous to the quantity $p'_{(Qd\ Lim)}$ derived in Equation (47) for the 'Qd' case, and having the same significance: the positions of points on Figs. 13 and 14 corresponding to practical lamp co-ordinates (p, p') are interpreted as in the case of Fig. 10.

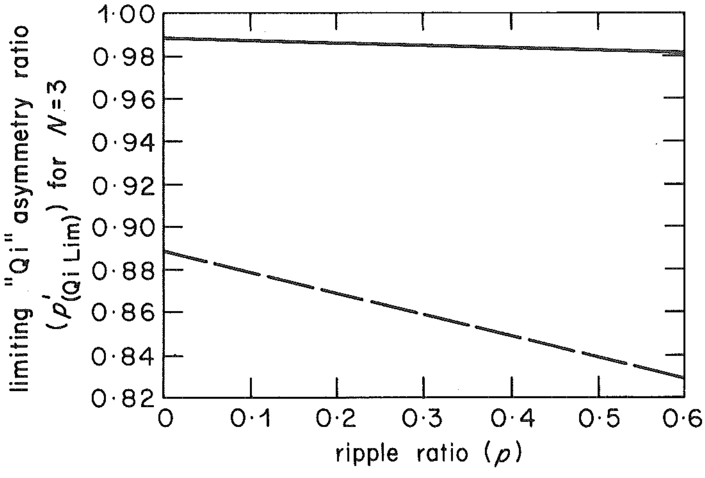

Fig. 14 - Limiting Q-independent asymmetry ratio, for N = 3
——— $R'_{E(Qi\ Lim)} = 48$ dB
– – – $R'_{E(Qi\ Lim)} = 28$ dB

TABLE 1

Summary of Effects of Ripple Asymmetry

Lamp supply frequency (Hz) to give f_L = 0, for indicated camera frame frequency (f_c)		f_c = 24 Hz	48	48	48	60	60
		f_c = 25 Hz	50	50	50	62·5	62·5
Camera shutter angle (deg) to give Q = 0			90	180	270	144	216
m			4	4	4	5	5
N			1	2	3	2	3
Frequency (f_L') of asymmetry luminance fluctuation frequency			$\sim\frac{f_L}{2}$	$\sim\frac{f_L}{2}$	$\sim\frac{f_L}{2}$	$\sim ½(f_p - f_L)$	$\sim ½(f_p - f_L)$
Figure numbers referring to magnitude of asymmetry luminance fluctuation component			11 + 13	9 + 10	12 + 14	9 + 10	12 + 14
Overall likely effect of asymmetry component for lamp having indicated values of ripple ratio (p) and asymmetry ratio (p')	p = 15%	p' = 90%	4	1	2*	3	4
		p' = 95%	3	1	1*	1	4
		p' = 98%	1	1	1*	1	3
	p = 40%	p' = 90%	4	1	1*	3	4
		p' = 95%	2	1	1*	2	4
		p' = 98%	1	1	1*	1	3

Scale used in rows 8–13: 1 - no effect. 2 - marginal effect. 3 - significant effect. 4 - very significant effect.
* applies if $f_L' < 0{\cdot}4$ Hz

frequencies in the range 45–65 Hz, it is essential to limit the value of Q (see footnote on p.4) so that the principal exposure variation component does not give rise to perceptible picture luminance fluctuations. In practice this involves operating with camera shutter angles[2f] near to the value for which $Q = 0$. Furthermore, since a larger amount of this picture luminance fluctuation component, and therefore a larger value of Q, can be tolerated when the fluctuation frequency is low, it is preferable to work near to the conditions for which the frequency (f_L) of the principal luminance fluctuation component is zero (see Equation (1)). The most favourable operating conditions occur when both these criteria are satisfied. Table 1 shows camera shutter angles,* lamp supply frequencies and camera frame frequencies for which these criteria are satisfied precisely (i.e. $Q = 0$ and $f_L = 0$). The corresponding values of m and N are also shown. The effects of these values of m and N (i.e. whether they are odd or even, and the particular odd values of N) are shown in rows 6–13. The comments in rows 8–13 are based on the author's rather limited experience of measurements of the light intensity ripple of practical metal-halide lamps operating within this lamp supply frequency range. In these measurements asymmetry ratios of 98% or greater could not be measured with any great accuracy, because of the finite width of the cathode-ray oscilloscope trace and the presence of noise from the photodetector amplifier, but there were indications that asymmetry ratios of this magnitude were not unusual. On present evidence, however, it appears that ratios lower than 95% seldom occur and that ratios lower than 90% are extremely unlikely. It may also be noted that, unlike the intensity ripple which is present at all times and whose magnitude is constant (for a particular lamp type and if operating conditions do not change), ripple asymmetry may appear, disappear and change in magnitude in a random manner, depending (presumably) on the points on each electrode from which the discharge emanates. Thus it is not possible, for example, to measure a small sample of lamps of a particular type and assess the magnitude of the asymmetry ratio, in the way that ripple ratio can be so assessed.

* Shutter angles lower than 90° or higher than 270° have not been included.

7. Conclusions

The effect of asymmetry in the intensity ripple component of light from a discharge lamp is to give rise to a component of picture luminance fluctuation in addition to the component produced by the presence of the ripple

itself. The relative visibility of these two components of luminance fluctuation depends on the relationships between the lamp supply frequency, camera frame frequency and camera shutter angle, as well as the magnitude of the ripple component itself and the amount of asymmetry present. In some circumstances the presence of ripple asymmetry is not likely to cause picture impairment over and above that caused by the ripple itself: hence if conditions are such that the effect of the ripple is imperceptible, then the effect of ripple asymmetry will also be imperceptible. These circumstances include the case where a camera frame frequency of 25 Hz, lamp supply frequency in the region of 50 Hz and a camera shutter angle of around 180° is used (i.e. normal U.K. practice for television filming). In other cases, however, luminance fluctuation effects due to ripple asymmetry may be visible even if conditions are such that the effect of fluctuations caused by the ripple itself is imperceptible: such cases include the use of a camera frame frequency of 24 Hz, a lamp supply frequency of about 60 Hz, and shutter angles around 144° or 216°. The use of the higher of these shutter angles is particularly disadvantageous in this respect.

Ripple asymmetry is not a parameter which is constant in magnitude for a given lamp type and particular operating conditions, but may vary with time in a random manner. Thus account may be taken of ripple asymmetry only on the basis of the worst case (i.e. greatest asymmetry or lowest asymmetry ratio) that experience shows is likely to be met with in practice.

8. References

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   1a. Ibid, Fig. 16.

2. TAYLOR, E.W. Some aspects of the use of metal-halide discharge lamps for film lighting. BBC Research Department Report No. 1976/2.
   2a. Ibid, Equation (6).
   2b. Ibid, Equation (14).
   2c. Ibid, Equation (16).
   2d. Ibid, Appendix.
   2e. Ibid, Equation (35).
   2f. Ibid, Equation (17).
   2g. Ibid, Equation (36).
   2h. Ibid, Equation (2).
   2i. Ibid, Equation (38).

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